Finnra

Use of Granulated Blast-Furnace Slag in Pavement Structures

Finnra Reports

18/1999

Oulu 1999

Finnra
Consultancy and
Construction R&D

Finnra Reports
18/1999

Use of Granulated Blast-Furnace Slag in Pavement Structures

Finnra
Consultancy and Construction R&D

Oulu 1999

ISSN 0788-3722
ISBN 951-726-532-8
TIEL 3200563E
Oy Edita Ab
Helsinki 1998

Publication and sale:
FinnRa
Telefax 0204 44 2202

YMPÄRISTÖMERKKI
MILJÖMÄRKT
441 057
Painotuote

Finnra
Opastinsilta 12 A
P.O. Box 33
FIN-00521 HELSINKI, Finland

Consultancy and Construction R&D
Vanhantullinkatu 2
P.O. Box 261
FIN-90101 OULU, Finland
Tel. +358 0204 44 6892

Use of granulated blast-furnace slag in pavement structures. Oulu 1999, Finnra, production, Finnra Reports 18/1999, xx s., ISSN 0788-3722, ISBN 951-726-532-8, TIEL 3200563E

Key words: granulated blast-furnace slag, road construction, pavement structure, by-products, frost protection, bearing capacity

ABSTRACT

Granulated blast-furnaceslag is a slowly binding, porous, sand-like by-product of iron works which is produced by granulation and can be used as a material for building the pavement structures of roads, for example. It reaches its dimensioned bearing capacity after one month under conditions of natural humidity. Cement can be used as an activator for accelerating the binding reaction. The granulated blast-furnaceslag layer also acts as a thermal insulation, thanks to its porous grain-size distribution, which can be taken into consideration when designing structural frost protection.

The load dimensioning of a granulated blast-furnaceslag structure proceeds in the same way as for conventional materials, in accordance with the pavement structure planning instructions employed by the Finnish Road Administration or in the form of a durability analysis based on loading-induced critical strains. The static elasticity modulus for granulated blast-furnaceslag, as determined in field and laboratory tests, is 600 MN/m^2. Dimensioning can also be performed using an analytical method in which the critical strain for the granulated blast-furnacelayer is represented by the transverse tension of the lower surface of the layer. The dynamic modulus value employed in the calculations is 800 MN/m^2. In cases where traffic is not allowed on the road until approximately a year after completion of the granulated blast-furnaceslag layer, higher modulus values, i.e. an elasticity modulus of 1000 MN/m^2 and dynamic modulus 1200 MN/m^2, can be used for dimensioning purposes, on account of the binding properties of the slag.

The frost dimensioning of structures incorporating granulated blast-furnaceslag can be performed by the methods traditionally employed in the Finnish Road Administration, or by an analytical method which allows frost heave as well as frost depth to be determined from the nature of the subgrade and the frost sum.

The granulated blast-furnaceslag layer is constructed on top of the filter layer and subgrade. Traffic can be allowed on the layer immediately after spreading and initial compaction. The pavement base should be made of crushed blast-furnaceslag or a mixture of granulated blast-furnaceslag and natural crushed aggregate in order to ensure proper adhesion between the pavement and the base. The road can be paved approximately a month after completion of the slag layer, this interval being necessary to ensure a sufficient degree of binding.

FOREWORD

The use granulated blast-furnaceslag in pavement structures has been based to date on the instructions given in the publication "Use of granulated blast-furnace slag in pavement structures" (Reports of the Finnish Road Administration 47/1994). A needs has now been perceived for revising these instructions, however, on the basis of experiences gained from the follow-up of test structures and changes in the production of granulated blast-furnaceslag.

The revision work was carried out jointly by SKJ-yhtiöt Oy, the supplier of granulated blast-furnaceslag, the Laboratories of Geotechnology and Road and Traffic Engineering at the University of Oulu, and the Oulu Development Unit of the Finnish Road Administration. The instructions were revised by Heikki Suni, Director of the Oulu Development Unit, Seppo Salmenkaita, Dipl.Eng, Marko Mäkikyrö, Vice President (Export) and Jari Lappi, Construction Manager with SKJ-yhtiöt Oy. The frost dimensioning calculations were performed by Teuvo Holappa, Dipl.Eng., of the Laboratory of Geotechnology, University of Oulu, and the load dimensioning calculations by Lauri Liimatta, Lic.Tech., of the Laboratory of Road and Traffic Engineering, University of Oulu.

The present publication is intended to replace that mentioned above as a guide to the use of granulated blast-furnaceslag in pavement structures.

Oulu, June 1999

Consultation

Oulu Development Unit

TABLE OF CONTENT

INTRODUCTION

A total of 550,000-600,000 tonnes of blast-furnaceslag is produced each year as a by-product of the iron works at Raahe and Koverhar in Finland. The majority of this slag is nowadays generated in granulated form as a result of water cooling.

Granulated blast-furnaceslag differs from conventional building materials in that it is porous, so that its most important features from the point of view of road construction are its thermal insulation capacity and binding properties. These properties can be exploited in the design of road structures by taking account of its advantageous effects on insulation and bearing capacity.

The first tests involving granulated blast-furnaceslag structures were carried out in Finnish Road Administration projects in the early 1990's, at which point actual dimensioning practises were created through laboratory research and development activity and an extensive experimental construction programme. Instrumented test structures were installed in high-quality main roads and in footpaths and cycle tracks.

The feedback obtained from these monitoring experiments has mainly been in line with the criteria laid down for both frost and bearing capacity dimensioning. The most problematic structures have proved to be ones with a high, narrow cross-section, in which the sides may not have been insulated at all. This has particularly been the case with footpaths and cycle tracks. Attention is also paid in the current instructions to the planning and functioning of drainage systems.

The present paper discusses the properties of granulated blast-furnaceslag as a material, looks into the planning of structures made of it and provides practical building instructions.

I PLANNING INSTRUCTIONS

1 PROPERTIES OF GRANULATED BLAST-FURNACESLAG AS A CONSTRUCTION MATERIAL

1.1 Manufacture of granulated blast-furnaceslag

Granulated blast-furnaceslag is an iron smelter by-product with a chemical composition which is determined by the blast-furnaceprocess and the raw materials and additives used in it.

The iron ore used in a blast-furnace contains iron oxide (hematite, Fe_2O_3, or magnetite, Fe_3O_4) and gangue materials, mainly oxides of silicon, calcium, aluminium and magnesium. Before the blast-furnaceprocess the fine-grained ore concentrate is converted to lumps by sintering, at which point coke or granulated carbon and lime are added.

The iron is released from its oxides in the blast furnace, i.e. it is reduced in the presence of coke at a high temperature. The coke itself contains approximately 88% carbon, about 10% ash from the gangue minerals and a small amount of sulphur.

When the blast-furnace temperature reaches 1400-1500°C, the gangue oxides and limestone melt to form a slag, which flows down into the chamber and forms a layer on top of the molten iron. The correct composition of the slag is decisive from the point of view of operation of the blast furnace, so that it should be maintained as carefully as possible.

Granulated blast-furnaceslag is the result of water cooling, which in the Raahe works is performed by conducting the molten slag at a temperature of approx. 1400°C from the blast-furnace directly into a pressurised water jet at approx. 8 bar. At Koverhar the slag (at approx. 1350°C) is poured from the sedimentation car into a pan into which water is injected at a pressure of 8 bar (Fig. 1). This pressurised water jet breaks the molten slag down into a product of grain size 0-5 mm which has excellent hydraulic and thermal properties.

Rapid cooling prevents the granulated blast-furnace slag from crystallising, so that it remains 98-100% in a porous, vitreous state.

Typical granularity curves for the typical granularity curves for the granulated blast-furnace slag (GBFS) manufactured at Raahe and Koverhar are shown in Fig. 2.

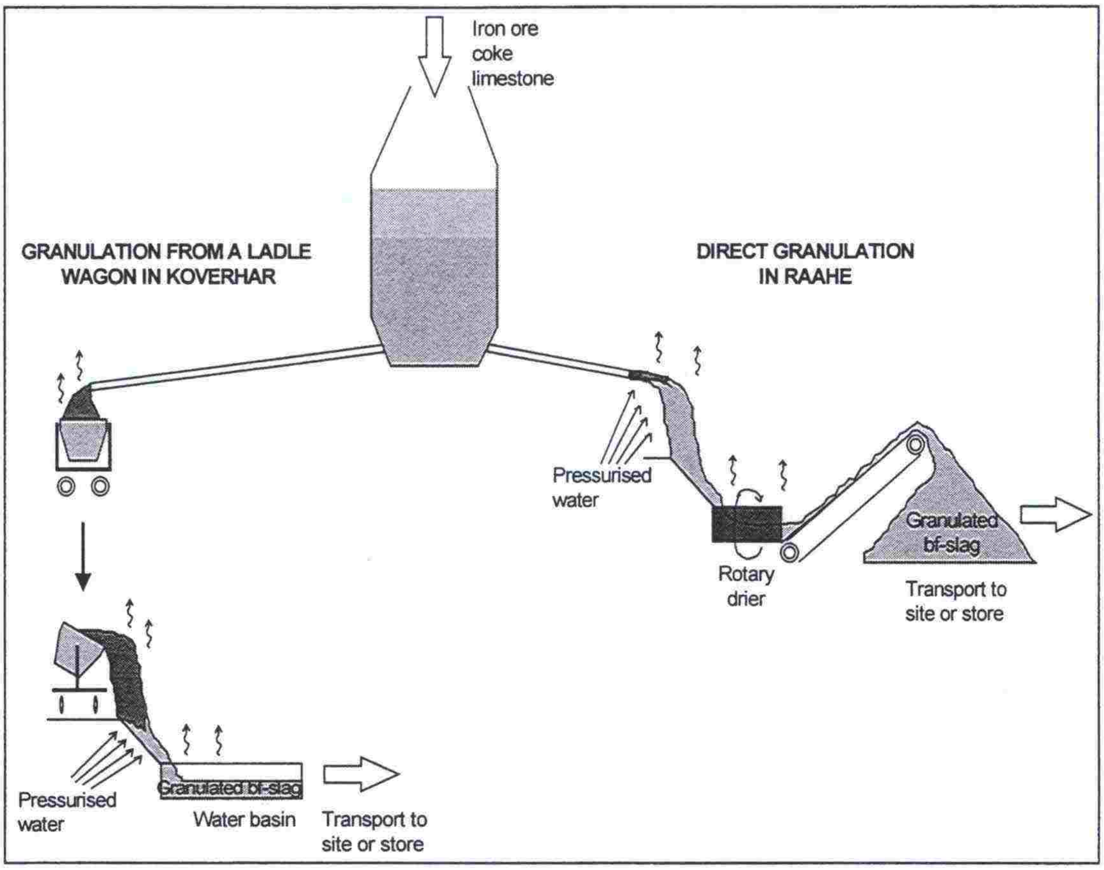

Figure 1: Manufacture of granulated blast-furnaceslag

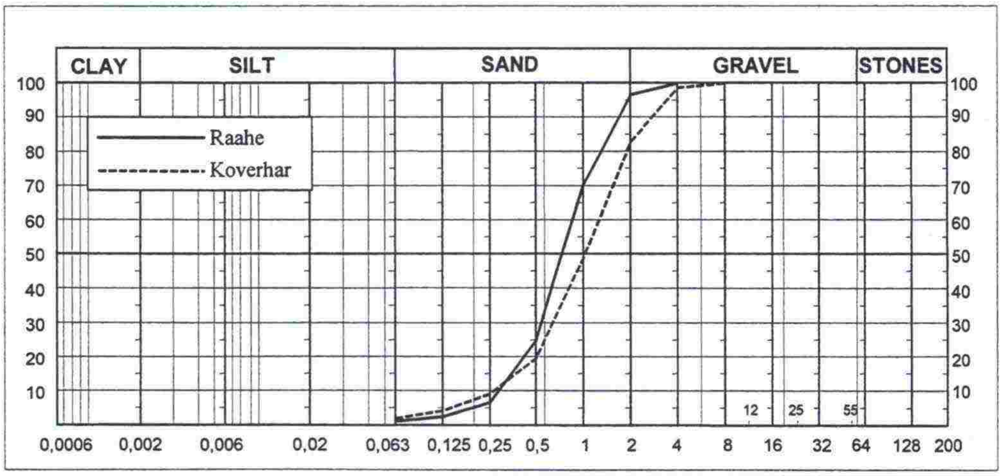

Figure 2: Typical granularity curves for the granulated blast-furnaceslag

1.2 Chemical properties of granulated blast-furnaceslag

1.2.1 Composition

The primary components of granulated blast-furnaceslag are oxides of silicon, calcium, aluminium and magnesium. Small amounts of sulphur, titanium, alkalis and manganese are also present, of which the sulphur in particular contributes significantly to its chemical properties.

These chemical properties are not dependent on composition only, but also on the vitreous, porous internal structure caused by rapid water cooling during the manufacturing process. The hydraulic properties of granulated blast-furnaceslag are attributable to its chemical composition and vitreous structure. Its average composition is indicated in Table 1.

Table 1: Chemical compositions of the granulated blast-furnace slags produced in Raahe and Koverhar.

Chemical compound	Granulated blast-furnaceslag from Raahe [%]	Granulated blast-furnaceslag from Koverhar [%]
CaO	35,6	32,6
MgO	11,0	15,8
SiO_2	37,7	32,6
Al_2O_3	9,49	12,2
K_2O	0,83	0,74
Mn	0,50	0,09
P	0,003	0,003
S_{tot}	1,41	2,06
Fe_{tot}	0,50	0,30
Zn	0,000	0,001

S_{tot} = total sulphur
Fe_{tot} = total iron

1.2.2 The binding reaction

Granulated blast-furnaceslag is bound hydraulically. The binding reaction is much slower than that of cement, and the binding temperature is considerably lower. Binding can be accelerated using cement and the reactions intensified further by reducing the grain-size through crushing.

Granulated blast-furnaceslag is capable of binding at a natural humidity without any additional activators. Binding is also promoted by the sulphur contained in it, most of which is in the form of calcium sulphide (CaS), which reacts with water to form calcium hydroxide ($Ca(OH)_2$), which in turn serves as an activator. The binding reaction occurs on the surfaces of the grains and advances to the new surfaces as these break down. Thus the material is capable of repairing its own cracks, which is important from the point of view of its structural life-span.

1.2.3 Environmental effects

Granulated blast-furnaceslag is a alkaline in composition and can be refined further to obtain a magnesium-rich liming material for agricultural use. Although it is not as soluble like limestone, it tends to neutralise an acid environment, particularly when in a fine-grained form.

It has a low acid-soluble sulphate content (less than 0.1%), as most of its sulphur is bound in calcium sulphide, as mentioned above. Thus the sulphur in this type of slag occurs in reduced form, although it may be slightly oxidized by air. This in turn may give rise to greenish compounds, some of which also have the typical smell of sulphur. This occurs more commonly with air-cooled blast-furnaceslag than with the water-cooled variety and has only a temporary impact.

Research conducted so far indicates that granulated blast-furnace slag does not contain heavy metals or any other toxic by-products, nor does it release any hazardous substances into the environment. According to a statement by the Technical Research Centre of Finland, granulated blast-furnace slag can safely be used for road building purposes in groundwater areas /1,2,15/.

1.3 Physical properties of granulated blast-furnaceslag

1.3.1 Volumetric weight

The bulk volumetric weight of granulated blast-furnaceslag is 10.0-11.5 kN/m^3 and its water content 5-10% of dry weight. Its theoretical volumetric weight based on its structure is 14.0-15.5 kN/m^3, and its maximum bulk volumetric weight determined by Proctor compaction is 15.0-15.5 kN/m^3.

1.3.2 Thermal properties

1.3.2.1 Thermal condustivity

The porosity conferred on granulated blast-furnaceslag by virtue of its mode of manufacture means that it also has good thermal properties.

Its thermal conductivity increases with water content, the figure for unbound granulated slag at 5-7% humidity being approx. 0.3 W/mK and that for the water-saturated form approximately 0.6-0.75 W/mK (Table 2). The thermal conductivity of fully water-impregnated granulated blast-furnaceslag is slightly greater in a frozen state than in a thawed one. Compacting and binding have only a minor impact on thermal conductivity /3,12/.

Variations in thermal conductivity as a function of saturation rate and temperature are indicated in Table 2.

Table 2: Thermal conductivity of bound and unbound granulated blast-furnace slag samples measured using a thermal conductivity sond /12/

Unbound samples							
Compaction	Water content	Thermal conductivity [W/mK]					
		-10 °C		0 °C		+22 °C	
		Raahe	Koverh	Raahe	Koverh	Raahe	Koverh
Medium compact	Operating humid.	0,27	0,34	0,20	0,28	0,28	0,33
Compact	Operating humid.	0,25	0,34	0,29	0,28	0,29	0,31
Medium compact	Saturated	1,08	1,32	0,97	0,78	0,59	0,70
Compact	Saturated	1,14	1,07	1,18	0,66	0,74	0,67
Bound samples							
Sample age	Water content	Thermal conductivity [W/mK]					
		-10 °C		0 °C		+22 °C	
		Raahe	Koverh	Raahe	Koverh	Raahe	Koverh
3 months	Operating humid.	0,23	0,32	0,20	0,32	0,28	0,32
6 months	Operating humid.	0,21	0,36	0,18	0,25	0,17	0,35
3 months	Saturated	1,15	0,98	0,54	0,79	0,65	0,58
6 months	Saturated	1,08	0,93	0,51	0,66	0,54	0,58

The degree of compaction of a medium-compact sample was 85-88% and that of a compact one 90-92%.

The operating humidity of the Raahe granulated blast-furnace slag was approx. 5% and that of the Koverhar slag approx. 7%.

The water content of the Koverhar slag in a saturated state was approx. 25% and that of the Raahe slag approx. 20%.

1.3.2.2 Thermal capacity

The specific thermal capacity of the granulated blast-furnaceslag produced by direct granulation in Raahe is 0.90 J/gK and that of the Koverhar slag 1.00 J/gK /14/. The principal factors affecting the thermal capacity are water content and the amount of ice present.

1.3.3 Hydraulic properties of granulated blast-furnaceslag

1.3.3.1 Capillarity

The capillary rise in granulated blast-furnaceslag varies from 0.10 to 0.20 m. Binding time and the degree of compaction do not have any appreciable impact on this capillary rise /12/.

1.3.3.2 Water permeability

Measurements based on artificial absorption (tension infiltration meter measurements) and standard pressure tests indicate that the water permeability properties of granulated blast-furnace slag are similar to those of natural sand, the result being $0.9x10^{-4}...1.5x10^{-4}$m/s. Binding does not influence water permeability /12/.

1.4 E modulus of granulated blast-furnace slag

Field tests suggest that a layer of granulated blast-furnace slag is capable of acting as a bound structure and that plate bearing capacities measured on top of such a bound layer are typically large, usually exceeding 1000 MN/m^2. The dynamic E moduli back-calculated from falling weight deflectometer readings varied in the range 800...2000 MN/m^2/13/.

The static E modulus value for the slag employed in load bearing capacity dimensioning is 600 MN/m^2 and the dynamic E value for use in analytical durability calculations is 800 MN/m^2. If the road is not taken into use until a year after construction of the slag layer, the corresponding values will be 1000 MN/m^2 and 1200 MN/m^2.

1.5 Granularity

The granularity of granulated blast-furnace slag is dependent on the slag temperature and the pressure of the cooling water. That of the material manufactured in Finland is within the range indicated in Fig. 3.

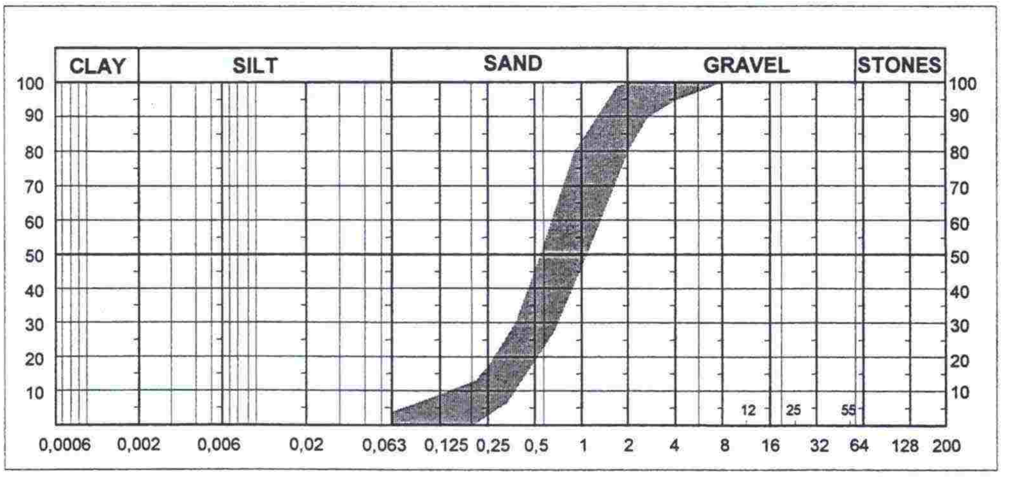

Figure 3: Nominal granularity range

1.6 Quality requirements

The physical properties and binding sensitivity of granulated blast-furnace slag vary according to its chemical composition and method of manufacture. The instructions given in the present publication apply to slags manufactured according to the description in Section 1.1, having chemical properties conforming to those listed in Section 1.2 and with a granularity in the range shown in Fig. 3.

2 PLANNING AND DIMENSIONING OF PAVEMENT STRUCTURES INCORPORATING GRANULATED BLAST-FURNACE SLAG

2.1 Principles of planning and dimensioning

The planning and dimensioning of structures containing granulated blast-furnace slag (Fig. 4) must be based on its technical properties, which differ from those of other building materials. Attention must is paid to thermal properties as far as ground frost is concerned and to the bearing capacity generated by its binding properties.

Frost dimensioning and bearing capacity dimensioning are discussed here with regard to both the traditional dimensioning method and the analytical method (Sections 2.5.1 and 2.5.2).

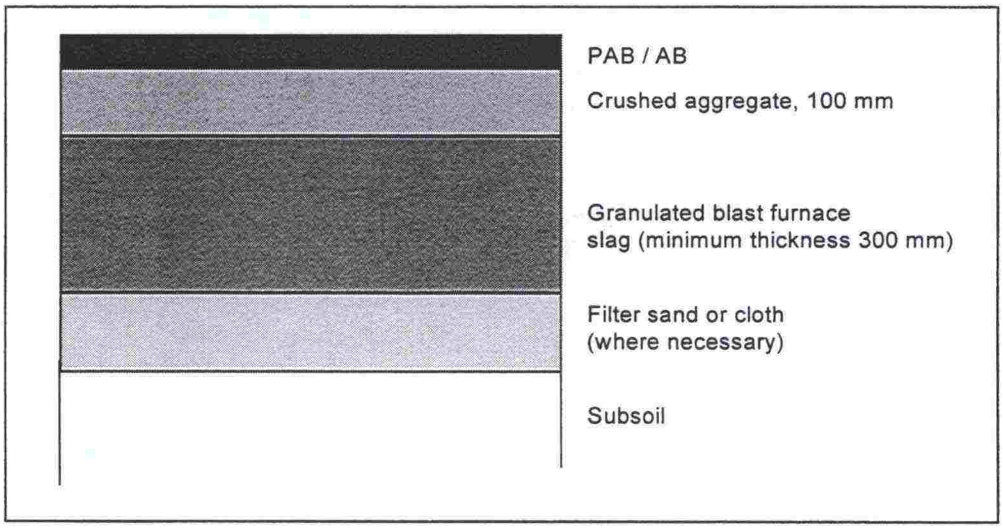

Figure 4: Road structure incorporating granulated blast-furnace slag

2.2 Drainage

Drainage should be arranged in accordance with the planning instructions laid down by the Finnish Road Administration /11/.

As the thermal conductivity of an insulated structure increases with water content, every effort should be made when planning the drainage of frost-protected structures containing granulated blast-furnace slag to follow the above drainage instructions.

2.3 Subgrade

The subgrade should be designed in accordance with the instructions laid down by the Finnish Road Administration /4/.

2.4 Pavement

2.4.1 Filter layer

The filter layer should be constructed in accordance with road design instructions. If the granulated blast-furnace slag is to serve as the filter layer, no separate thickness provision needs to be taken into consideration when dimensioning this layer.

If there is a danger of mixing of the subsoil and filter layers, a filter cloth should be employed between them.

Any old structural layers left beneath the replaced material in the case of road improvement will act as a filter layer.

2.4.2 Granulated blast-furnace slag layer

The slag layer beneath the pavement will act as a bound, load-distributing thermal insulation layer. Frost dimensioning should be performed as stated in Section 2.5.1 and load dimensioning as in Section 2.5.2.

A slag structure similar to a displacement wedge should be inserted at each end of the slag layer to act as a frost insulation element, in accordance with the special instructions provided by the Finnish Road Administration, ensuring that the structure is of the correct layer thickness at the desired point.

As a granulated blast-furnace slag layer has good thermal insulation capacities, frost may appear on top of the pavement in some situations, usually in autumn, which is not the case with conventional road structures. This may pose a traffic safety problem, particularly if short stretches of road are constructed with slag.

2.4.3 Pavement base

The purpose of the pavement base is to ensure proper contact between the pavement and the base and to facilitate the passage of traffic before the actual pavement is laid. This layer may be composed of:

- crushed blast-furnace slag of grain size 0-10…32 mm, layer of thickness 100 mm or
- non-humic natural crushed aggregate of grain size 0-18...32 mm, layer thickness 100 mm, containing 10-15 wt% granulated blast-furnace slag /5,10/.

Pure, unmixed natural crushed aggregate can be used on footpaths and cycle tracks.

2.5 Dimensioning

2.5.1 Frost dimensioning

Frost dimensioning will be discussed here with regard to both the conventional method in use at the Finnish Road Administration and the analytical method. The former determines the thickness of the granulated blast-furnace slag layer on the basis of degrees below zero and permitted frost penetration, while the latter allows frost depth and frost heave to be determined on the basis of the subsoil and the frost sum. **The minimum slag layer thickness is 300 mm.**

2.5.1.1 Frost dimensioning principles

Structural displacement occurs as a result of subsoil freezing and thawing, which manifests itself in the form of cracks and unevennesses on the road surface. Thawing of the frozen soil in spring impairs the load bearing capacity of the subgrade. The major principle in frost dimensioning is to examine freezing from both a technical and an economic perspective. The costs arising from restricting freezing should be in correct proportion to the likelihood of damage, the resulting defects and the costs of repairing the damage. Frost dimensioning is used as a means for restricting frost heave differences in order to reduce surface unevenness and cracks. The reduced bearing capacity after the thawing of the frost in spring must also be taken into consideration when calculating bearing capacity. Frost dimensioning sets out from the category of the road concerned and the prevailing soil and groundwater conditions /6/.

The figure for the operating humidity of granulated blast-furnace slag used in the dimensioning calculations is 7%. The thermal conductivity of granulated and crushed blast-furnace slag was estimated on the basis of laboratory tests, that of soil was calculated by Kersten's method and volumetric thermal capacity and deformation temperature from the dry density and water content. The subsoil segregation potential with a 0 load used in the frost-heave calculations was 1...10 mm^2/Kh. The calculations were based on average monthly temperatures. The average monthly temperatures for the winter of dimensioning were calculated on the basis of the normal winter distribution by adjusting the average normal monthly temperatures by the coefficient F_{mit}/F_N (frost sum of dimensioning winter/normal frost sum).

2.5.1.2 Dimensioning based on frost depth

Frost depth is greatly affected by frost conditions and drainage. A thermal insulation structure made of granulated blast-furnace slag can be dimensioned by restricting frost depth beneath the slag layer, in accordance with the planning instructions of the Finnish Road Administration. The thickness of the layer can then be selected from Table 3, depending on subsoil humidity.

A humidity of 26% indicates a humid subgrade/subsoil and 12% a dry one. The subsoil in the calculations is frost-susceptible till. It should be borne in mind when evaluating the effects of frost depth that a high water content increases the specific heat capacity of the material, thus slowing down the penetration of frost into the material. On the other hand, even slight freezing of the material may give rise to major frost heave if a sufficient amount of water is available at the frost front.

Layer thicknesses are grouped in Table 3 according to the amount of frost to be allowed for and the humidity of the subgrade/subsoil. Intermediate values can be interpolated in a linear manner. The resulting layer thickness must be rounded upwards to the nearest 50 mm.

The thickness of the granulated blast-furnace slag layer should be determined mainly by procedures based on permitted frost heave (Section 2.5.1.3).

Table 3: Determining the thickness (h) of the granulated blast-furnace slag layer on the basis of frost penetration into the structure beneath it.

Permitted penetr. beneath the GBFS layer [mm]	Humidity w [%]	Frost sum F_{mit} [Kh] 20 000 h [mm]	30 000 h [mm]	40 000 h [mm]	50 000 h [mm]	60 000 h [mm]
	26 %	650	900	1100	1250	1450
0	19 %	650	900	1100	1250	1450
	12 %	650	900	1100	1250	1450
	26 %	350	500	650	800	950
200	19 %	400	600	750	950	1100
	12 %	450	650	850	1050	1200
	26 %	---	300	450	550	650
400	19 %	300	450	550	700	850
	12 %	350	550	700	850	1000
	26 %	---	---	300	400	500
600	19 %	---	300	400	550	700
	12 %	300	400	550	700	850
	26 %	---	---	---	300	400
800	19 %	---	---	300	450	550
	12 %	---	300	450	550	700
	26 %	---	---	---	---	300
1000	19 %	---	---	---	350	450
	12 %	---	---	350	450	600
	26 %	---	---	---	---	---
1200	19 %	---	---	---	300	350
	12 %	---	---	300	350	500

2.5.1.3 Dimensioning based on permitted frost heave

Frost heave is usually calculated using numerical models based on a combination of mass and thermal transfer. These can be used to calculate displacement during and after freezing, and humidity and temperature as a function of time and place.

Modelling soil freezing and thawing requires an analysis of the interrelations between parameters describing the preservation of matter and energy, displacement of heat and water, and soil properties. The most widely used numerical frost heave calculation model is the CRREL model.

Frost heave has also been calculated using the concept of segregation potential /7/, which describes the intensity of freezing. This concept is derived from experimental measurements showing that the amount of water flowing into the ice lens is directly comparable to the prevailing frozen layer temperature gradient, in accordance with equation (2).

$$v(t) = SP(t) \times gradT(t) \qquad (2)$$

in which	gradT(t)	is	temperature gradient of the partly frozen layer
	v(t)		rate of frost heave
	SP(t)		segregation potential

Segregation potential can be determined by means of laboratory frost heave tests or in-situ measurements, provided that the temperature gradient of a partly frozen soil layer and the speed by which water flows to the freezing front are known (or the rate of frost heave is known). The flow velocity of the soil water can be calculated on the basis of the rate of frost heave by considering the expansion of water, the porosity of unfrozen soil and the amount of unfrozen water at the segregation temperature. Frost depth can be calculated by the conventional methods for layered structures.

The magnitude of the segregation potential is dependent on the properties of the soil type and condition factors (loading, groundwater table). Segregation potential values typically encountered in Finnish soils, as determined in laboratory frost heave tests, are indicated in Table 4. **A frost heave test is recommended in demanding and uncertain cases, in order to ensure the correctness of the segregation potential.**

Table 4: Segregation potentials for different soil types, as determined in frost heave tests.

Soil type	Segregation potential SP_O [mm^2/Kh]
Clay	3,5...10,0
Silt	2,0...7,5
Sand	0,1...1,0
Till	2,0...6,0

The frost dimensioning of roads can then be performed on the basis of the permitted frost heave and the frost sum selected for dimensioning purposes. Curves for determining the thickness of granulated blast-furnace slag in the above manner are indicated in Figs. 5a and 5b.

It should be noted that the frost heave values employed in dimensioning indicate orders of magnitude only. **Thus the slab effect for a bound slag structure, which may reduce frost heave substantially, is not taken into consideration.** Exact calculations require the use of numerical models, and such methods are still at the development stage with regard to practical frost dimensioning.

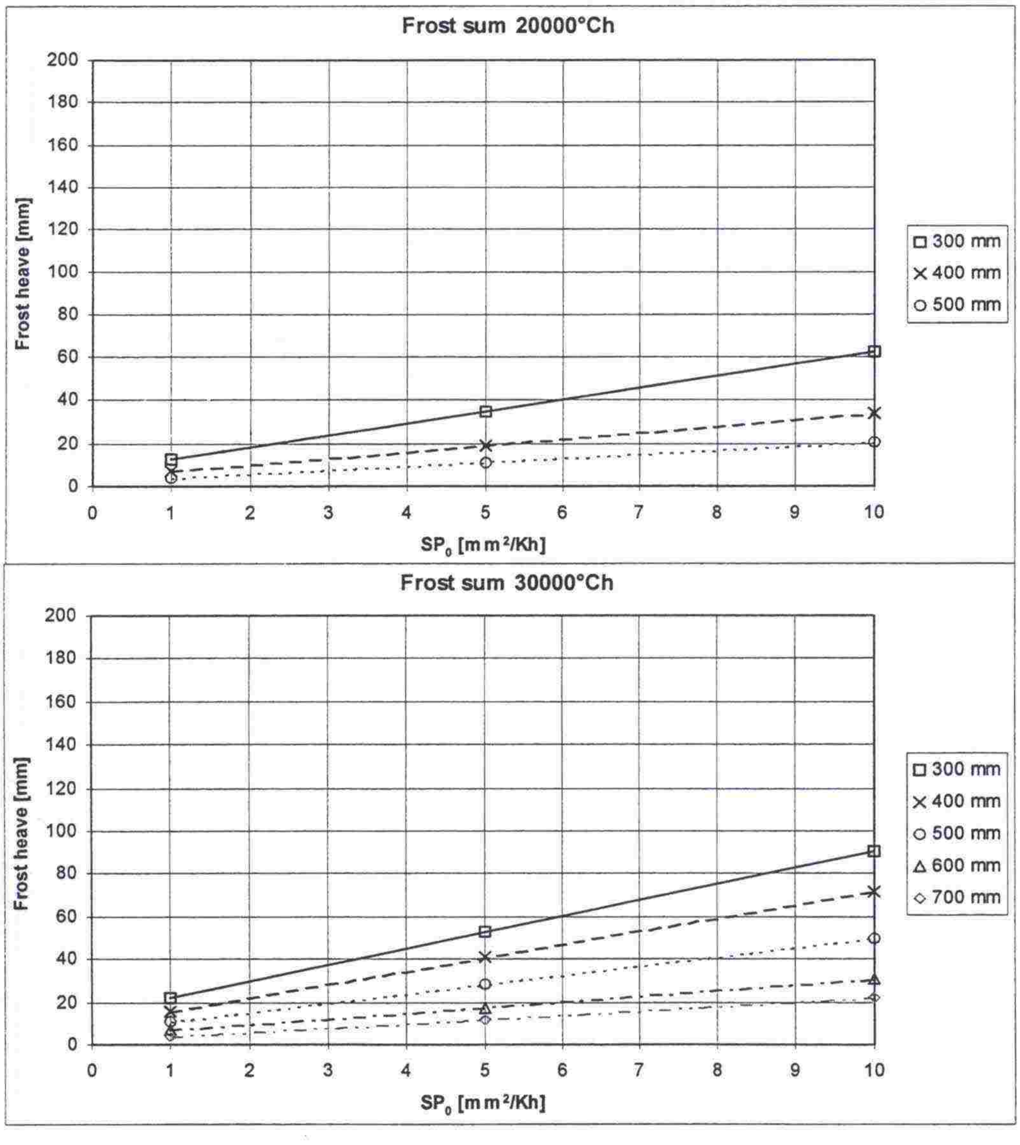

Figure 5a: Frost heave in a road structure containing granulated blast-furnace slag as a function of frost, subsoil freezing (SP_0) and thickness of the slag layer.

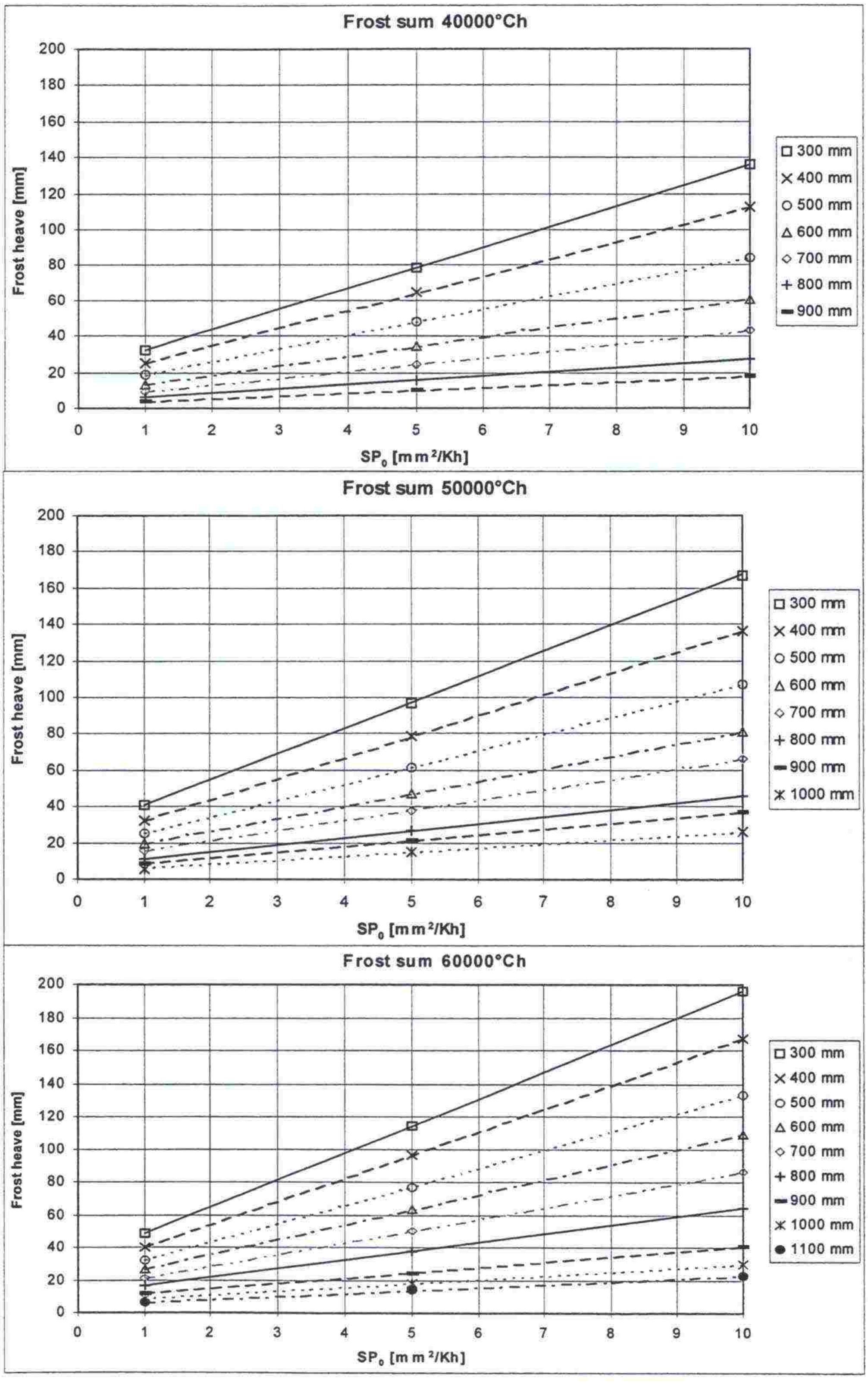

Figure 5b: Frost heave in a road structure containing granulated blast-furnace slag as a function of frost, subsoil freezing (SP_0) and thickness of the slag layer.

2.5.2 Load dimensioning

Granulated blast-furnace slag can be regarded as an intermediate form between a bound and unbound material. It differs essentially from soil cement, for example, in terms of its behaviour in road structures. Cement-bound materials are characterised by tensions caused by shrinking, and the target bearing capacity of semi-rigid cement-bound structures is at least 60 MN/m^2 greater than that of conventional structures. The durability criteria developed for rigid cement-bound structures cannot be applied directly to structures containing granulated blast-furnace slag, due to the exceptional behaviour of the latter. In the case of traditional load dimensioning, the increased target bearing capacity determined for semi-rigid structures should be employed.

Load dimensioning for granulated blast-furnace slag can also be performed in the traditional bearing capacity manner (Figs. 6 and 7) or in the form of durability tests based on the critical strain imposed by traffic loads (Figs. 8 and 9). The thicknesses of the granulated blast-furnace slag layer represented by the curves in these diagrams refer to joint thicknesses of the slag and the layer of crushed aggregate above it. **The minimum thickness of the slag layer is 300 mm.**

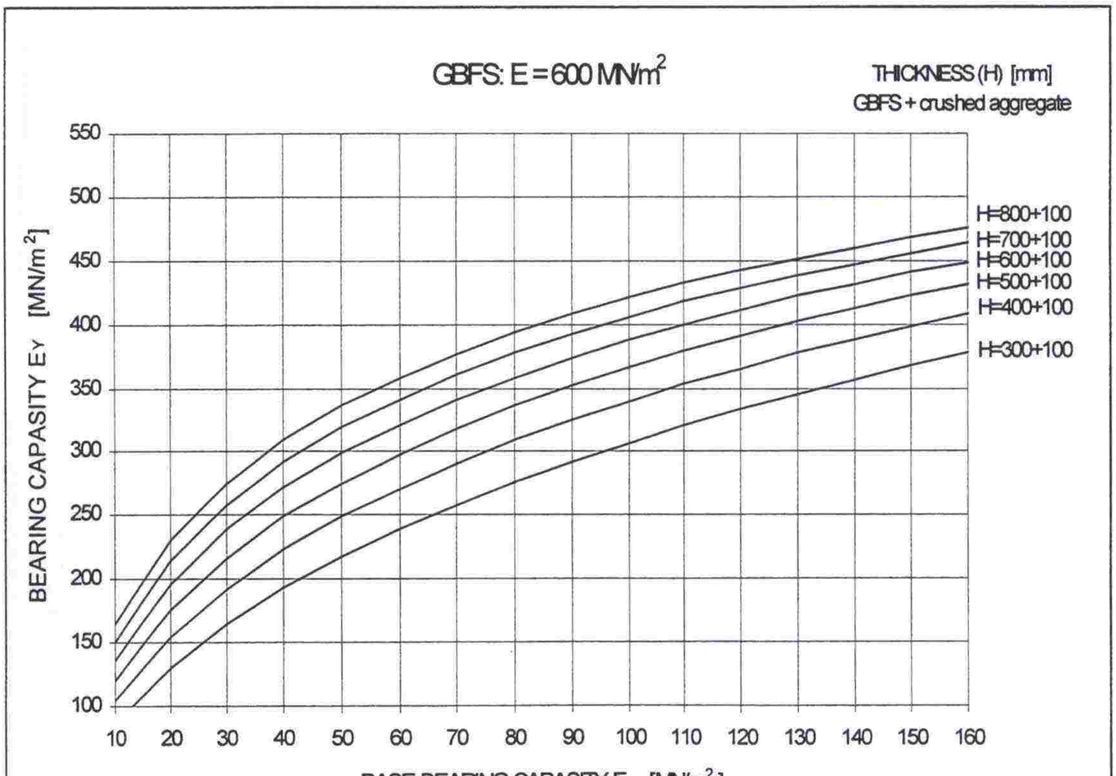

Figure 6: Bearing capacity dimensioning with granulated blast-furnaceslag for which E = 600 MN/m^2.

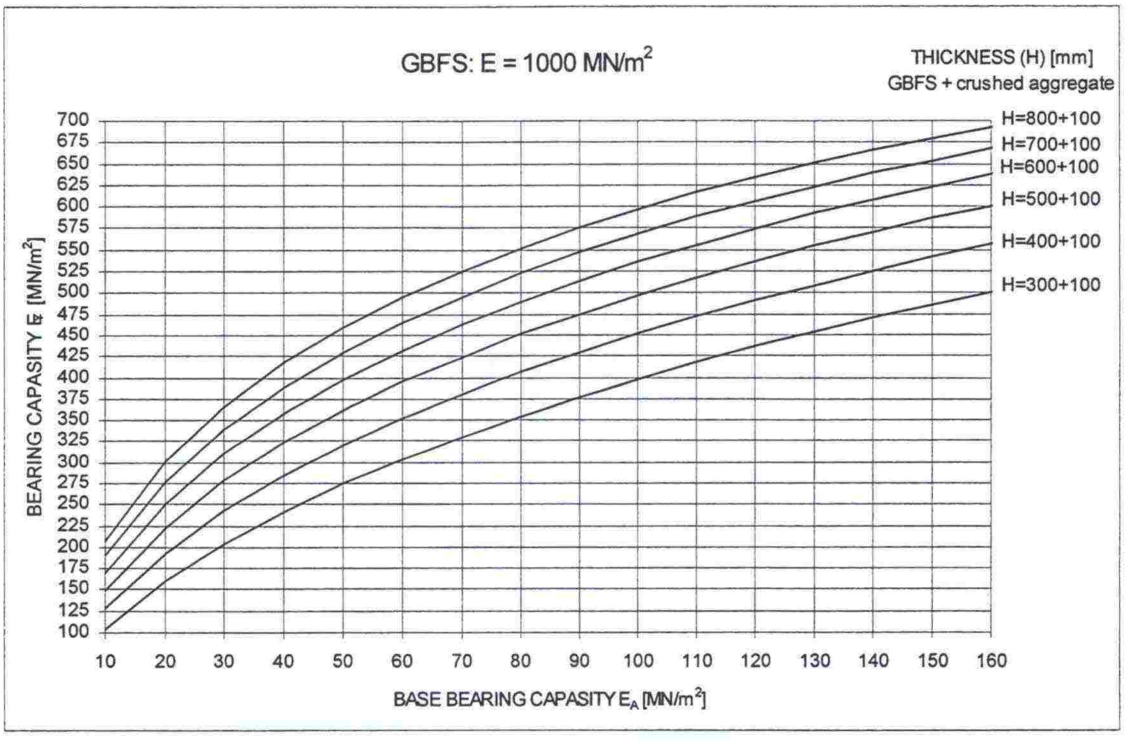

Figure 7: *Bearing capacity dimensioning with granulated blast-furnaceslag for which E = 1000 MN/m².*

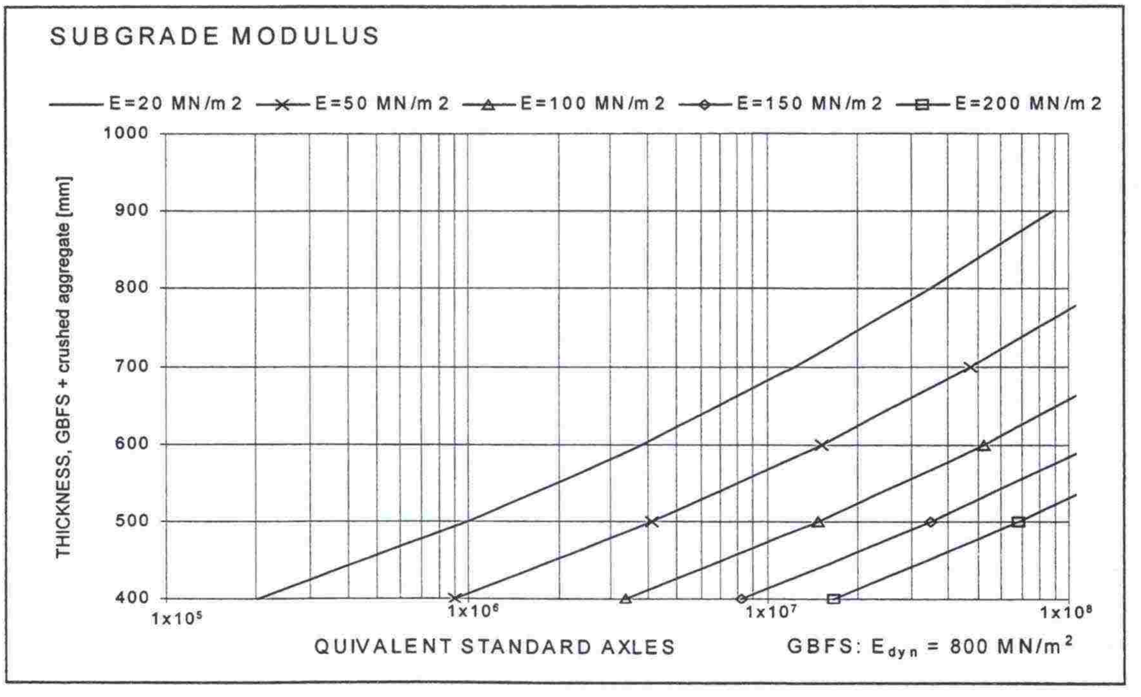

Figure 8: *Bearing capacity dimensioning by reference to tension/ deformation analysis with granulated blast-furnace slag for which E = 800 MN/m². The figure applies to the case described on page 23.*

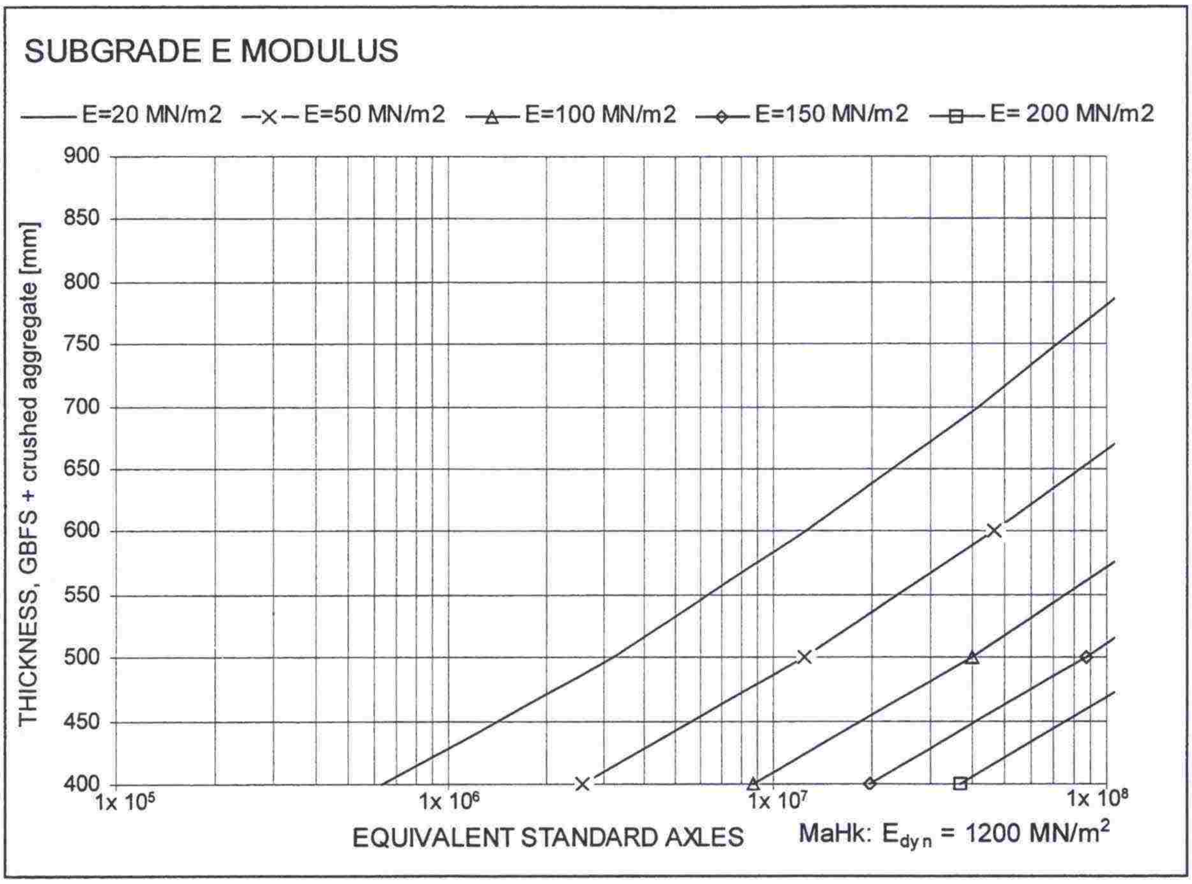

Figure 9: Bearing capacity dimensioning by reference to tension/ deformation with granulated blast-furnace slag for which E = 1200 MN/m². The figure applies to the case described on page 23.

Bearing capacity dimensioning follows the principles contained in the planning instructions of the Finnish Road Administration /8/. These set out from bearing capacity of the subgrade, the type of material and the target bearing capacity.

The static elasticity modulus for granulated blast-furnace slag is taken here to be 600 MN/m². If vehicles are not allowed on the slag structure until approximately a year after its completion, a value of 1000 MN/m² can be used for design purposes.

The bearing capacity of the slag layer can be obtained from the subgrade bearing capacity and slag layer thickness, as indicated by the dimensioning curves (Figs. 6 and 7).

Another alternative is the analytical procedure. The tension/deformation analysis referred to these instructions sets out from the notion of restricting the compression deformation of the layer beneath the slag. This criterion was developed by the Asphalt Institute, and its permitted base compression deformations are the smallest of all the durability criteria currently in use. The dimensioning is conducted using the Shell Bisar program, which involves calculating the critical strain and deformations caused by the wheel load on the road. The critical strain for structures containing granulated blast-furnace slag is the bending tensile strain imposed on the lower surface of the slag layer. The dynamic modulus used in the calculations is 800 MN/m^2 and 1200 MN/m^2.

The dimensioning criterion for granulated blast-furnace slag is the permitted base compression deformation (Asphalt Institute), see Ullidtz P., Pavement Analysis. Restricting the compression deformation of the layer beneath the slag also restricts the tensions arising at the lower surface of the actual slag layer.

Analytical dimensioning uses a dynamic E modulus for the slag layer base, which is usually determined by means of a CBR test or a dynamic triaxial test. The soil type classification used by the Finnish Road Administration for determining the bearing capacity of different types of soil as part of overall dimensioning is shown in Table 5, together with the corresponding USCS classification and soil type E moduli.

The dimensioning curves in Figs. 8 and 9 were obtained in such a way that the thickness of the slag layer can be dimensioned on the basis of equivalent standard axles and the E modulus of the base of the slag layer. The pavement material is assumed to be AB 50 mm. A dynamic E modulus of 800 MN/m^2 is used when traffic is allowed on the layer immediately after its completion, but a value of 1200 MN/m^2 can be accepted if vehicle loads are not allowed until approximately one year after completion of the layer.

Table 5: Subgrade bearing capacity and E modulus for given soil types.

Bearing capasity dimensioning **Subgrade bearing category**				**Analytical dimensioning** **Classification of base E modulus according to soil type**	
SOIL TYPE	DETAILED DESCRIPTION	CATEGORY	BEARING CAPASITY MN/m²	CATEGORY	BASE E-MODULUS MN/m²
Bedrock	rock blasted rock crushed rock	A	300	GW	300
Stones		A	300		
Gravel		B	200 (150..280)	GP	300
Gravelly till	non-frost-susceptible frost-susceptible	C E	100 (70..150) 20 (15..35)	GM, GC	200 50
Sand	coarse non-frost-susc mid-coarse non-frost-s fine non-frost-susc mid-coarse frost-susc. fine frost-susceptible	C D D (E) E E (F)	100 (70..150) 50 (35..70) 50 (35..70) 20 (15..35) 20 (15..35)	SW SP SP SM, SC SM, SC	200 100 100 50 50
Sandy till	non-frost-susceptible frost-susceptible	D (E) E (F)	50 (35..70) 20 (15..35)	SP SM, SC	100 50
Silt Silty till		F (G, E) F (G, E)	10 (5..15) 10 (5..15)	OL OL	20 20
Clay	dry shell tough soft	E F (E) G	20 (15..35) 10 (5..15) 5	CL OL MH-OH	50 20 10
Gyttja Peat		G G	5 5	Pt Pt	10 10

2.6 Dimensioning example

Let us consider the dimensioning of a pavement using granulated blast-furnace slag, the initial values being:

- road quality requirement: 1
- new road
- subsoil: sandy till
- frost sum F = 40,000°Ch
- permitted frost heave: 30 mm
- pavement structure category: 1 AB
- structural dimensioning age: 20 years
- equivalent standard axles: 1.0×10^7.

Frost dimensioning

As the point of departure here is the permitted frost heave, the calculated can be carried out example by analytical dimensioning (Fig. 10).

As the segregation potential of sandy till has not been determined by means of a frost heave test, the potential should be selected from Table 4, which gives Sp_o =3.0 mm^2/Kh.

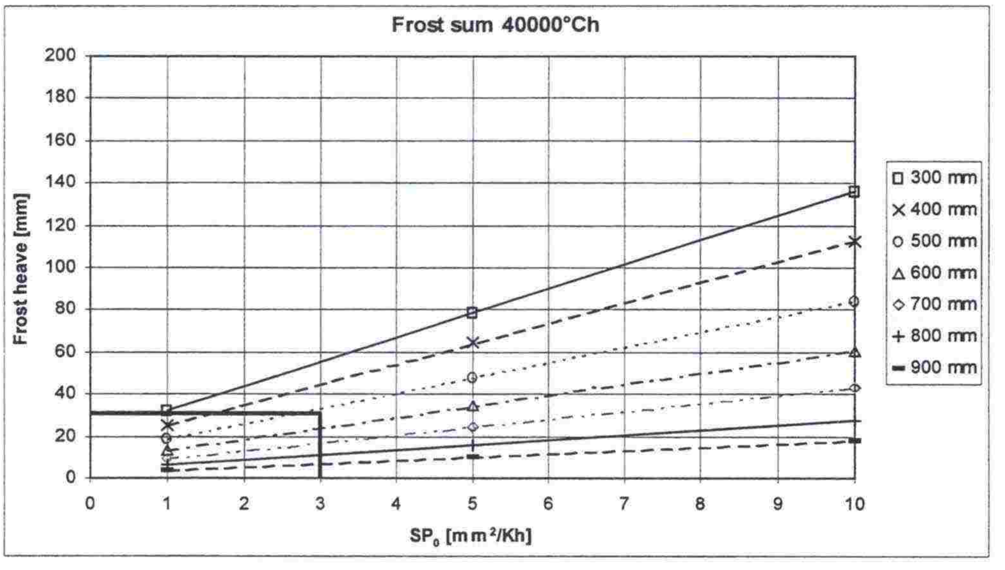

Figure 10: Frost dimensioning by the analytical method (dimensioning example)

As shown in Fig. 10, the thickness of the slag layer for a 30 mm permitted frost heave is 550 mm (frost sum 40,000°Ch). Together with the 100 mm layer of crushed aggregate to be used as the pavement base, the total thickness of the slag structure is 650 mm.

Load dimensioning

Load dimensioning is performed by the traditional method in accordance with Fig. 11.

The bearing capacity requirement for ordinary structures in the pavement structure category 1 AB is 160 MN/m^2, measured on top of the base course /8/, and the base bearing capacity is 20 MN/m^2 in cases where the subsoil is composed of sandy till (Table 5). If we accept the suggestion that the target bearing capacity should be incremented by 60 MN/m^2 for semi-rigid structures, traditional dimensioning yields a figure of 220 MN/m^2. As we are dealing here with a new road, it can be assumed that traffic will be allowed on the road only after the year following the completion of the slag layer, so that a modulus of 1000 MN/m^2 is used in the dimensioning.

The total thickness of the granulated blast-furnace slag structure is thus (500+100) i.e. 600 mm (Fig. 11).

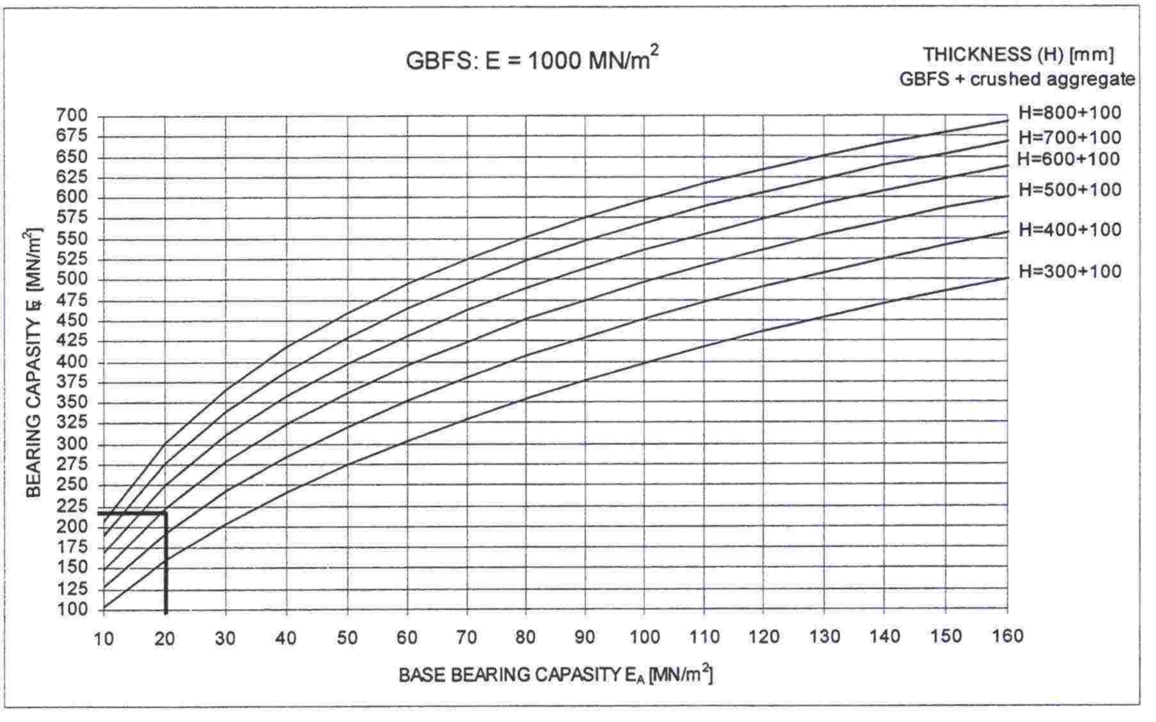

Figure 11 Traditional load dimensioning (dimensioning example)

If we set out to determine the bearing capacity by the analytical dimensioning method, by means of Fig. 12, we start out from a dynamic E modulus of 50 MN/m^2 for the base (Table 5). The value for equivalent standard axles is 1.0 x 10^7, so that according to Fig. 12, the thickness of the slag structure should be 490 mm.

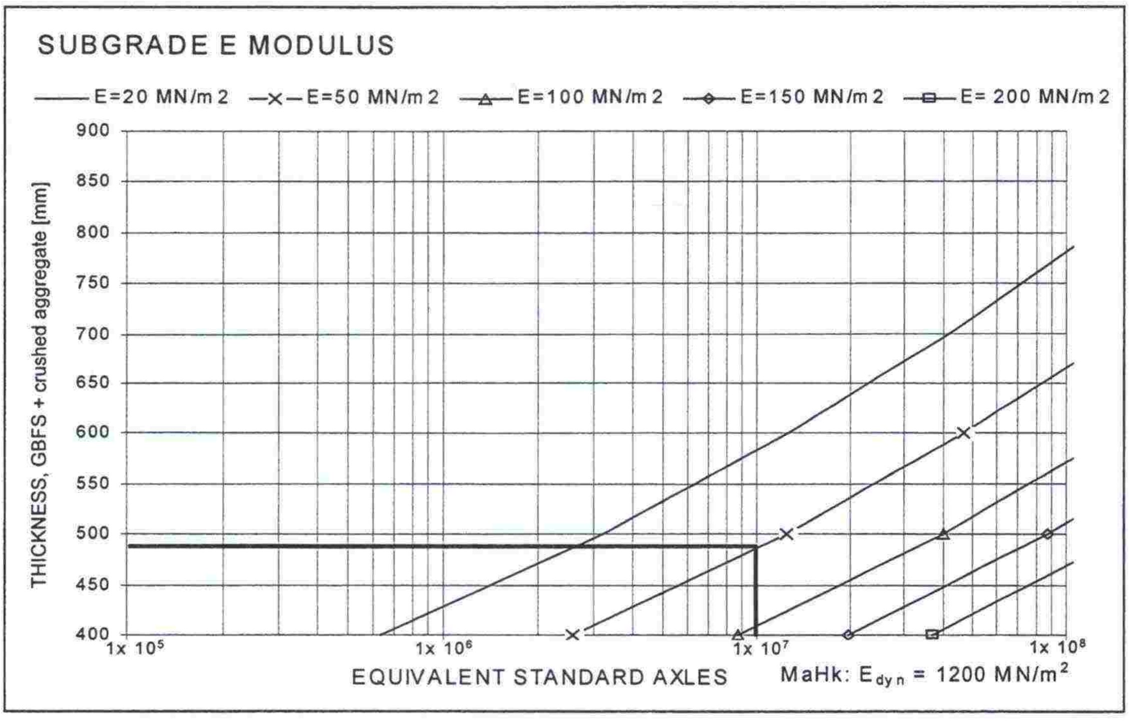

Figure 12: Analytical load dimensioning (dimensioning example)

Thus frost dimensioning yields a slag layer thickness of 650 mm, traditional load dimensioning 600 mm and analytical load dimensioning 490 mm.

The following structure should thus be employed:

- AB 50 mm
- crushed blast-furnace slag or natural crushed aggregate 100 mm
- granulated blast-furnace slag 550 mm.

The decisive factor in the above example was the frost dimensioning. Comparing the result for this with the corresponding result of analytical load dimensioning it is evident that the structure is over-dimensioned with regard to bearing capacity, so that its service life will clearly exceed the stated target.

II CONSTRUCTION PROCEDURES

1 APPLICABILITY OF THE INSTRUCTIONS

The present instructions apply to pavement structures in which granulated blast-furnace slag is used for improving bearing capacity and/or as a thermal insulation material.

2 STORAGE AND TRANSPORTATION

Granulated blast-furnaceslag can be stored unprotected provided that it is not subjected to the weight of heavy-duty machines during storage. Long-term storage or compaction during storage may give rise to caking of the material, however. Slight caking does not present any appreciable difficulties in the case of solid structures, as the cakes break down upon spreading and compaction. Short-distance transport close to the construction site can be accomplished with trucks and long-distance transport preferably by barge or ship.

3 DRAINAGE AND SUBGRADE

The quality requirements and work specifications commonly employed in road construction should be followed as far as drainage is concerned. Measures should be taken to ensure at the building stage that no depressions that accumulate water or barriers that may prevent it from flowing out of the slag layer are left in the subgrade.

The quality requirements and work specifications commonly employed in road construction should be followed in the preparation of the subgrade.

4 PAVEMENT STRUCTURE

4.1 Road and street structures

4.1.1 Filter layer

The filter layer should be constructed in accordance with the general quality requirements and work specifications employed in road building. If the layer is composed of granulated blast-furnace slag, it should be constructed in connection with the slag layer proper. A filter cloth should be installed in accordance with the instructions.

When adding thermal insulation to an old pavement, the old layers should be removed in such a way that the slag layer constructed on top of it will be of equal thickness throughout. The surface of the layer remaining beneath the slag should fall within the limits set for permitted deviations in the subbase in the general road building quality requirements and work specifications, Table 6 /9/.

Table 6: Permitted deviations in the subbase /9/

Permitted deviations	
LOCATION OF THE LEVEL	
- deviation in location of the level	± 100 mm
- change in deviation in location	100 mm / 20 m
LEVEL	
- individual deviation perpendicular to the surface	± 30 mm
- change in individual deviation	30 mm / 20 m
- deviation of average for the level perpendicular to the surface	± 15 mm
DIMENSIONS	
- individual deviation in width of upper surface	± 60 mm
- mean deviation in width of upper surface	± 30 mm
GRADIENT	± 1,0 %-units
MEAN THICKNESS OF LAYER	- 5 mm
EVENNESS MEASURED USING A STRAIGHT EDGE	30 mm / 5 m

4.1.2 Granulated blast-furnace slag layer

The slag layer acts as a bound load-distributing thermal insulation layer beneath the pavement.

A slag structure corresponding to a transition wedge should be constructed at each end of the slag layer in the manner shown in the plan.

4.1.2.1 Construction

The slag layer is constructed as an end embankment on top of the filter course. The maximum thickness of one layer before compacted should be 500 mm. A slag layer can also be constructed in winter provided that the frost-susceptible subsoil beneath the filter course is not substantially frozen. Care should be taken not to mix snow or ice into the slag layer during construction. If the subsoil is frozen, the slag layer can only be constructed in summer, once the frost has thawed. The filter course should then be efficiently post-compacted.

Loaded trucks can be allowed on the layer after levelling and light machine compaction, provided that the levelling is performed using a blade grader or wheel loader. Traffic can also be allowed on the layer during the road construction work. The surface of the layer should be adjusted to its final level and form and compacted 2-4 times using a smooth roller. This compaction will facilitate the passage of traffic during the work.

4.1.2.2 Quality requirements for granulated blast-furnace slag layers

Steps should be taken to ensure upon acceptance of the material at the site that it meets the quality requirements and that no caking that could hamper construction of the slag layer has taken place during storage.
It should also be checked when constructing the layer that the quality referred to in this work specification is achieved.

The properties of granulated blast-furnace slag are such that the required bearing capacity will not be achieved immediately on construction of the layer. Binding will cause the bearing capacity to reach virtually its final level in 2-3 months during the summer, however.

4.2 Footpaths and cycle tracks

Footpaths and cycle tracks are problematic, particularly if embankments are employed, as frost may penetrate beneath the slag structure through the slopes of the embankment. To prevent this, narrow roads of width less than 5 m should be protected with granulated blast-furnace slag in the manner shown in Fig. 13. This should be done whenever the height of the embankment measured from the bottom of the ditch exceeds one metre (H>1 m).

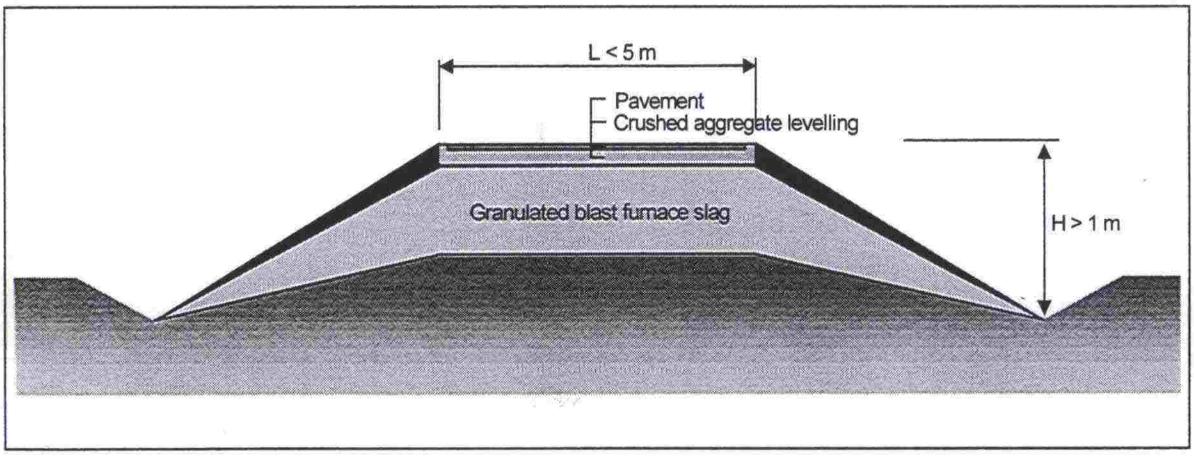

Figure 13: Principle for a granulated blast-furnace slag structure in a combined footpath and cycle track with a high embankment.

A thin layer of crushed aggregate (approx. 50 mm) should be employed as the base for the pavement without mixing it with the slag layer (the humus content of the material is of no significance in such a thin layer). The surface should be compacted using a tyre roller (2-3 times) or vibration roller (twice).

Footpaths and cycle tracks can be paved immediately after construction of the layers if necessary, as the loads on them are small.

4.3 Pavement base

The surface of a granulated blast-furnace slag layer always contains some loose slag which tends to be set in motion as the asphalt is spread and thus prevent proper contact between the pavement material and the base. Thus a thin layer of crushed aggregate or crushed blast-furnace slag should always be placed on top of the slag layer proper. This layer should be constructed in accordance with the permitted deviations allowed for the base course by the general road building quality requirements and work specifications, Table 7 /9/.

4.3.1 Natural material as a pavement base

A 100 mm layer of non-humic crushed aggregate of grain size 0-18...32 mm is spread on top of the layer of granulated blast-furnace slag and mixed into the surface using a miller or else a 20-30 mm layer of granulated slag is spread on the top of the aggregate layer using a sand sprinkler, for example, and mixed into the underlying aggregate by means of a blade grader with a tube blade during the process of levelling. The surface should be compacted with a vibration or tyre roller (2-3 times). This mixing facilitates the passage of traffic during the construction phase and reduces the need for levelling.

If crushed aggregate in a humus category of 2 or more in the NaOH test is used, the humic effect should be neutralised with the amount of cement proposed in the plan /10/.

4.3.2 Crushed granulated blast-furnace slag as a base for the pavement

A 100 mm layer of granulated blast-furnace slag of grain size 0-10...32 mm may be spread prior to laying of the pavement, levelled to its final form and compacted using a tyre roller (2-3 times) or vibration roller (twice). The surface will becomes compact and bound under traffic loading.

Table 7: Permitted deviations in the base course /9/

Permitted deviations	
LOCATION OF THE LEVEL	
- deviation in location of the level	± 100 mm
- change in deviation in location	100 mm / 20 m
LEVEL	
- individual deviation perpendicular to the surface	± 20 mm
- change in individual deviation	20 mm / 20 m
- deviation of average for the level perpendicular to the surface	± 10 mm
DIMENSIONS	
- individual deviation in width of upper surface	± 60 mm
- mean deviation in width of upper surface	± 30 mm
GRADIENT	± 0,5 %-units
MEAN THICKNESS OF LAYER	- 5 mm
EVENNESS MEASURED USING A STRAIGHT EDGE	20 mm / 5 m

4.4 Paving

The road can be paved approximately a month after completion of the granulated blast-furnace slag layer. Before paving, the surface should be roughened with a grader equipped with a tube blade and then compacted using a tyre roller (1-2 times) or a smooth roller (once).

The bearing capacity requirements for the pavement base are contained in general quality requirements and work specifications. The slag layer should be moistened before paving so as to promote binding.

5 TRAFFIC DURING CONSTRUCTION

Traffic can be allowed on the slag layer immediately after its spreading and initial compaction. On account of its manner of production, granulated blast-furnace slag does not contain any fine matter that would create dust, so that scarcely any dust binding is required.

A pavement base composed of granulated blast-furnace slag is well capable of withstanding even long-term traffic loads. Any surface repairs should be performed using a grader with a tube blade. If dust binding is required, conventional methods and agents can be employed.

REFERENCES

1. Sorateiden kelirikkovaurioiden korjaaminen, väliraportti III: Materiaalitutkimuksia jalostetuista teollisuuden sivutuotteista. 1992. Kuopio. 76 s. Tielaitos, Kuopion tuotantotekninen kehitysyksikkö. (Tiehallituksen sisäisiä julkaisuja 51/1992)

2. Kloridin liukeneminen kuonasta. Tutkimusraportti. 1993. Rautaruukin tutkimuskeskus.

3. Harju-Antti, P. & Viljas, P. 1993. Masuunihiekan lämpötekniset ja hydrauliset ominaisuudet. Oulu. 31 s. (Oulun yliopiston geotekniikan laboratorion julkaisuja nro 15. ISBN 951-42-3615-7, ISSN 0785-2142

4. Alusrakenne. Julk.: Tie- ja vesirakennushallitus. Teiden suunnittelu. TVL:n ohjeet. Helsinki. Kansio B osa IV.

5. Päällystetyn tien parantaminen. Sitomattomien kerrosten käyttö. Rakenteen parantaminen. Julk.: Tie- ja vesirakennushallitus. Teiden suunnittelu. TVL:n ohjeet. Helsinki. Kansio B osa IV.

6. Alusrakenne. Routimisen rajoittaminen. Julk.: Tie- ja vesirakennushallitus. Teiden suunnittelu. TVL:n ohjeet. Helsinki. Kansio B osa IV.

7. Konrad, J.M. 1980. Frost heave mechanics. Ph.D. Thesis University of Edmonton Alberta. 472 s.

8. Päällysrakenne. Julk.: Tie- ja vesirakennushallitus. Teiden suunnittelu. TVL:n ohjeet. Helsinki. Kansio B osa IV.

9. Penger- ja kerrosrakenteet. Tienrakennustöiden yleiset laatuvaatimukset ja työselitykset. 1994. Helsinki. 62 s. ISBN 951-47-8747-1, TIEL 2212460-94

10. Masuunihiekkastabilointi. Tielaitoksen selvityksiä 13/1996. Oulu 1996. 27 s. ISBN 951-726-192-6, TIEL 3200382

11. Kuivatus. Julk: Tielaitos kehittämiskeskus. TVL:n ohjeet, Helsinki. Kansio B Teiden suunnittelu, osa IV. Tien rakenne 4.

12. Raahen ja Koverharin masuunihiekkojen tekniset ominaisuudet (loppuraportti). Kuonat geotekniikassa-projekti. Tutkimusraportti 6/96. Oulu 1996.

13. Liimatta L. Taipumamittausten käyttö tien rakenteellisen kunnon arvioimisessa. Oulun yliopisto. Lisensiaatin työ 1996.

14. Masuunihiekan lämpökapasiteetin määritys. VTT Rakennustekniikka. Tutkimus-selostus nro RTE 11008/97. Espoo 12.2.1997. 2 s.

15. Masuunihiekan käyttö tierakenteissa pohjavesialueilla. VTT Yhdyskuntatekniik-ka. Lausunto nro 14/7/96 - YKI52. Espoo 28.10.1996. 6 s. + liitteet.

LITTERATURE

Jydycki, J. 1991. Strustural characterization of road base materials treated with hydraulic binders. Oulu. 111 s. (Oulun yliopiston tie- ja liikennetekniikan laboratorion julkaisuja nro 12). ISBN 951-42-3162-7, ISSN 0785-4137

Turunen, R. et al 1990. Asfalttipäällysteisten teiden päällysrakenteiden mitoitusmenetelmät. Oulu. 89 s. (Oulun yliopiston tie- ja liikennetekniikan laboratorion julkaisuja nro 7)

Liimatta, L. et al 1992. Teiden kuormituskestävyys/parantamistarpeen laskenta. Oulu. (Oulun yliopiston tie- ja liikennetekniikan laboratorion julkaisuja nro 19.)

Maarakennusalan tutkimus- ja suunnitteluohjeita, osa I. 1970. Helsinki. 328 s. Tie- ja vesirakennushallitus.

Masuunikuonan käyttö sitomattomissa päällysrakennekerroksissa. 1993. Oulu. 29 s. Tielaitos, Geokeskus, Oulun kehitysyksikkö (Tielaitoksen selvityksiä 15/1993) ISBN 951-47-6987-2, TIEL 3200142.

Ullidtz, P. 1987. Pavement Analysis. Amsterdam. Elsevier Science Publishers B.V. 318 s. ISBN 0-444-42817-8.

ISSN 0788-3722
ISBN 951-726-532-8
TIEL 3200563E